165-179 AU 346 48408

EP 0114640
AUG 1984

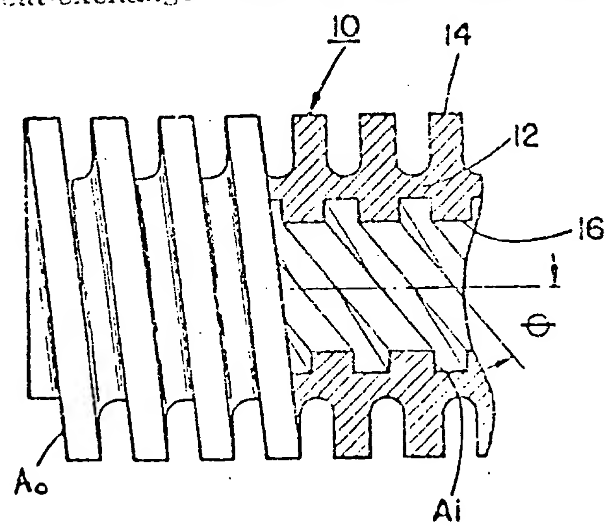
GULW ☆ Q78 84-190462/31 ★EP -114-640-A
Finned heat-exchanger tube for optimal heat transfer - by correlation of external and internal fin areas in conformance with predetermined mathematical criteria

GULF & WESTERN IND 25.01.83-US-460784

X27 (01.08.84) F28f-01/42

17.01.84 as 100427 (1455CG) (E) No-SR.Pub E(BE DE FR GB IT NL SE)

A metallic heat-exchanger tube (10) has a cylindrical wall (12)



with integral external and internal fins (14,16), both of helical configuration. Experimentally the external heat transfer area (Ao) per unit length of the tube, the internal heat transfer area (Ai) per unit length, the cross-sectional flow area and the lead angle (theta) of the internal helix are dimensioned for optimal heat-transfer performance in boiling a refrigerant with 8 to 10 deg.F of superheat.

The ratio of the internal fin area to the square foot of the cross-section is between 4.25 and 6.2. The ratio of the external and internal fin areas is between 1.5 and 5. The lead angle of the internal fin is between 40 and 60 deg.

USE - In direct-expansion evaporators of mechanical refrigerators. (18pp Dwg.No.1/2)

N84-142360

(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: 0 114 640
A2

(12) EUROPEAN PATENT APPLICATION

(21) Application number: 84100427.8

(22) Date of filing: 17.01.84

(51) Int. Cl.³: F 28 F 1/42

(30) Priority: 25.01.83 US 460784

(43) Date of publication of application: 01.08.84 Bulletin 84/31

(84) Designated Contracting States: BE DE FR GB IT NL SE

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(54) **Finned heat exchanger tube having optimized heat transfer characteristics.**

(57) A metal heat exchanger tube which provides for optimized heat transfer characteristics and which is particularly adapted for use in the direct expansion shell and tube type evaporators of mechanical refrigeration systems. The metal heat exchanger tube incorporates integral external and internal fins wherein the dimensional and geometrical proportions of the surface or heat transfer areas of the external and internal fins and the cross-sectional flow area of the heat exchanger tube, in conjunction with the lead angle of the internal helical fins have been correlated in conformance with predetermined mathematical criteria in order to optimize the heat transfer capacities of the tubes, particularly when the tubes are to be employed in direct expansion evaporator of mechanical refrigeration systems.

EP 0 114 640 A2

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FINNED HEAT EXCHANGER TUBE HAVING OPTIMIZED HEAT TRANSFER CHARACTERISTICS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a metal heat exchanger tube which provides for optimized heat transfer characteristics and, more particularly, relates to an integrally finned metal heat exchanger tube which is particularly adapted for use in the direct expansion shell and tube evaporators of mechanical refrigeration systems.

Heat exchanger elements, such as metal tubes which are employed for heat transfer purposes and which may constitute components of direct expansion shell and tube evaporators for mechanical refrigeration systems, are well known in the art; particularly in configurations wherein the tubes are plain, in essence, are unfinned and have essentially smooth bores. Heretofore, in order to improve upon the heat transfer properties of such metal heat exchanger tubes, the tubes have, in general, been provided with a plurality of integral internal fins transverse of the length of the tubes in a parallel spaced or helical pattern, thereby increasing the internal heat transfer surface area of the tubes and improving the heat transfer capabilities thereof. Although such internally finned heat exchanger tubes evidence improved heat transfer characteristics in comparison with plain or unfinned tubes, in essence, tubes which do not possess any internal fins, the degree of improvement in heat transfer capability over unfinned tubes is still insufficient to achieve the potential optimum heat transfer capacity of such heat exchanger tubes.

Consequently, more recently, finned metal heat exchanger tubes have been developed for this type of

refrigeration technology wherein the addition of external integral fins has been incorporated into the physical geometries of the heat exchanger tubes for the purpose of still further enhancing the heat transfer capacities of the tubes. Numerous analytical investigations and actual physical experiments have been undertaken in the industry with regard to correlating the dimensions and configurations of the heat exchanger tubes and those of the integral external and internal tube fins in order to attempt to optimize, or at least improve upon, the heat transfer characteristics of such finned heat exchanger tubes. For this purpose, extensive mathematical formulae have been developed in the heat exchanger technology, through the application of which there are derived metal heat transfer tube configurations, particularly for metal heat exchanger tubes which are adapted to be employed in the direct expansion shell and tube evaporators of mechanical refrigeration systems, and wherein the formulae are predicated upon relatively predictable parameters, such as the operating conditions of the system, type of heat exchange fluids being conducted within and externally of the heat exchanger tubes, and upon the actual external and internal dimensions and configurations of the heat exchanger tube.

Although considerable efforts have been expended in the technology in attempting to obtain an optimization of externally and internally finned heat exchanger tubes in order to achieve improved heat transfer properties, at best, the results have only been partially successful in achieving the desired goals.

2. Discussion of the Prior Art

Basically, in calculating the geometrical dimensions and/or physical criteria in the design of

externally and internally finned metal heat exchanger tubes having potentially optimized heat transfer characteristics, particularly tubes which are to be employed in the direct expansion shell and tube evaporators of mechanical refrigeration systems, various operating and physical parameters are taken into consideration. These parameters may be summarized as follows:

Ao	=	External tube area per foot of length	(ft^2/ft)
Ai	=	Internal tube area per foot of length	(ft^2/ft)
Aix	=	Internal tube cross sectional flow area	(ft^2)
ϕ	=	Severity factor Ref. "Heat Transfer Characteristics of Helical-Corrugated Tubes For Intake Boiling of R-12", Withers, J.G. and Habdas, E.P. Wolverine Tube Div., UOP. Presented at 47th National Meeting of AIChE	
θ	=	Lead angle of internal integral fin reference longitudinal tube axis	Degrees
ΔP	=	Refrigerant Pressure Drop	(psi)
Q	=	Heat Transfer Rate	(BTU/hr)
A	=	Total heat exchanger external area	(ft^2)
MTD	=	Mean effective temperature difference	(°F)
U	=	Overall heat transfer coefficient	(BTU/hr ft^2°F)

An extensive discussion of finned metal heat exchanger tubes of the type disclosed in U.S. Patent No. 3,826,304 is set forth by James G. Withers and Edward P. Habdas in Paper No. 87d presented at the 47th National Meeting of the American Institute of Chemical

Engineers, New Orleans, LA, March 11-15, 1973, entitled "Heat Transfer Characteristics of Helical-Corrugated Tubes for Intube Boiling of Refrigerant R-12". Although the article describes the intended optimization of internally ridged (finned) heat exchanger tubes, notwithstanding the complex theoretical calculations involved, no criteria can be ascertained which would readily lead to or support the attainment of tube dimensions or geometries providing optimized performance characteristics in the employment of the tubes in the direct expansion shell and tube evaporators of mechanical refrigeration systems within the normal operating ranges of such systems. Consequently, although various design methods have been developed with respect to the provision of externally and internally finned heat exchanger tubes, which may present performance improvements over plain or unfinned tubing for use in direct expansion evaporators, the prior art heat exchanger tubes and design methods are not in the optimum range for maximum heat transfer. Thus, externally and internally finned tubes have been designed for use in direct expansion evaporators in which the heat transfer capacity of these tubes is limited by the geometrical relationships of the external and internal fin surface areas and the internal flow cross-section of the tube, without taking into consideration the lead angle of the internal helical fins and any correlation of these tube dimensions. Consequently, these tubes are not designed for operation within the optimum range for maximum heat transfer.

Other design methods for heat exchanger tubes employed for intube boiling of refrigeration systems are not suitable for optimization of the tube configurations with respect to maximum heat transfer. Specifically, in these methods, the so-called severity factor of the tubing is not

dependent upon the lead angle of the internal helical fins of the tubes, whereas extensive investigation pursuant to the present invention indicate that the heat transfer capacity is an important function of the lead angle of the internal helical fins of the tubes. Moreover, prior art finned tubes have severity factors which are outside of the "optimum range" for the particular inventive application, and previously described heat exchanger tube design methods are not applicable to optimization of direct expansion evaporator applications. Moreover, the geometrical relationships of presently known and commercially available externally and internally finned tubes, particularly with respect to the correlation among the surface areas of the external and internal fins and the flow cross-sectional areas of the tubes, fall outside the optimum range for maximum heat transfer capacity of the tubes.

Other design data currently employed in the technology is adapted for tubes having either plain (unfinned) or slightly knurled outer surfaces, and wherein it can be ascertained that the addition of external fins to the tubes significantly improves their heat transfer capacities. Such design methods, in general, do not take into consideration the geometrical or physical interrelationships of the heat exchanger tube dimensions and, in many instances, the methods are not adapted for superheating applications, which is most likely encountered in the operation of direct expansion evaporators.

Among various currently known finned heat exchanger tubes, a number of these come into consideration with respect to the inventive concept, although none of the prior art tubes are designed for or adapted to optimization of the extent of the heat transfer of the tubes.

Thus, Lord et al. U.S. Patent 4,118,944 disclose an internally finned heat exchanger tube wherein the fin configuration is selected so as to restrict the temperature drop of the refrigerant in the tube to within a preselected range as the refrigerant flows therethrough. The dimensions of the finned tubing disclosed in Lord et al. clearly indicates, both as to the configuration of the helical internal fins, and the lack of any external fins which may be integrally formed with the tube that the heat exchanger tubes disclosed therein would not be suitable for optimization of the maximum heat transfer range, particularly when the tube is to be employed in the direct expansion evaporator of a mechanical refrigeration system.

Withers Jr., et al. U.S. Patent 3,847,212 disclose an externally finned metal heat transfer tube which includes helical ridging (finning) on the inner diameter of the tube so as to provide for improved heat transfer capabilities. However, review of the calculations and physical dimensions and geometry of this heat exchanger tube construction clearly evidences that there is no correlation in evidence between the surface or heat transfer areas of the external and internal tube fins, the flow cross-sectional area of the heat exchanger tube and the lead angle of the internal helical fins which would provide for optimization of the maximum heat transfer capacity of the tube in a manner analogous to that contemplated by the present invention. In essence, the heat exchanger tubing disclosed in Withers Jr., et al. does not provide for optimum maximum heat transfer capability, particularly when the tubes are to be employed in direct expansion shell and tube evaporators for mechanical refrigeration systems.

Similarly, Thorne U.S. Patent 3,881,382, Rieger U.S. Patent 3,768,291 and Goodyer U.S. Patent 2,432,308 each disclose externally and internally finned metal heat exchanger tubes. However, as in the above-discussed instances, none of these tubes evidence nor suggest geometric and dimensional interrelationships among the external and internal fins, the flow cross-sectional area of the tube and the lead angle of the helical interior fins which would provide for optimization of the heat transfer capacity of such tubes to thereby render these highly efficient when employed in direct expansion evaporators, particularly evaporators utilized for mechanical refrigeration systems.

SUMMARY OF THE INVENTION

Accordingly, in order to obviate the limitations and drawbacks encountered in metal heat exchanger tubes designed and contructed pursuant to the prior art, and particularly heat exchanger tubes which are designed for utilization in the direct expansion shell and tube evaporators of mechanical refrigeration systems, pursuant to the present invention the metal heat exchanger tubes incorporate integral external and internal fins wherein the dimensional and geometrical proportions of the surface or heat transfer areas of the external and internal fins and the cross-sectional flow area of the heat exchanger tubes, in conjunction with the lead angle of the internal helical fins have been correlated in conformance with predetermined mathematical criteria in order to optimize the heat transfer capacities of the tubes, particularly when the tubes are to be employed in direct expansion evaporator of mechanical refrigeration systems.

The inventive heat exchanger tube design and construction is based on actual experimental test data gathered from direct expansion coolers in refrigeration

systems incorporating various correlated combinations of the external and internal finned heat exchanger surface areas, cross-sectional flow areas of the tube, and the lead angle of the internal fins, which will lead to optimized heat transfer characteristics.

Specifically, the Bo Pierre boiling and ΔP equations which were published during the 1950's and which are referred to in the article by James G. Withers and Edward P. Habdas, Paper No. 87d, entitled "Heat Transfer Characteristics of Helical-Corrugated Tubes for Intube Boiling of Refrigerant R-12", presented at the 47th National Meeting of the American Institute of Chemical Engineers, New Orleans, LA, March 11-15, 1973, have been inventively modified to account for the lead angle of the internal helical tube fins and the hydraulic diameter of an internally finned tube. In calculating the optimum physical parameters for the heat exchanger tube pursuant to the invention, these modifications have been added to the known general heat transfer equation $Q = U \times A \times MTD$. A relationship has been found which allows for the coupling of the modified heat transfer and ΔP equations within the general equation, as expressed in terms of the physical dimensions of the heat exchanger tube as set forth hereinabove. This relationship remains valid for values of the internal cross-sectional flow area of the heat exchanger tube, or the hydraulic diameter, which are optimal over the normal operating range of direct expansion evaporators of mechanical refrigeration systems as currently employed in the industry.

More specifically, optimal interrelationships have been found between the external and internal heat transfer surface areas of the tube fins, the internal cross-sectional flow area of the heat exchanger tube, and the lead angle of

the internal helical tube fins. Thus, specific optimal operating ranges have been found, pursuant to the invention, at lead angles of between about 30 to 60° for the internal helical tube fins measured relative to the longitudinal axis of the tube, with such geometrical relationships not at all having been heretofore contemplated or employed in prior art heat exchanger tube structures.

Accordingly, it is a primary object of the present invention to provide for a finned metal heat exchanger tube of the type described which optimizes the heat transfer characteristics due to its physical parameters.

A more specific object of the present invention resides in the provision of a metal heat exchanger tube having integral external and internal helical fins wherein the physical dimensions of the external and internal tube fins, the lead angle of the internal fins, and the cross-sectional flow area of the tube are correlated with each other to provide for optimum heat transfer capacities, particularly when the tube is to be employed in the direct expansion shell and tube evaporator of a mechanical refrigeration system.

BRIEF DESCRIPTION OF THE DRAWINGS

Reference may now be had to the following detailed description of a finned metal heat exchanger tube, in which the tube is particularly adapted to provide for optimized heat transfer characteristics when employed as a component in direct expansion evaporators for mechanical refrigeration systems; taken in conjunction with the accompanying drawings; in which:

Figure 1 illustrates a longitudinal view, partly in section, of an externally and internally finned heat exchanger tube pursuant to the invention; and

Figure 2 is a cross-sectional view taken along line 2-2 in Figure 1.

DETAILED DESCRIPTION

Referring now in detail to the drawings, a metal heat exchanger tube 10 having a cylindrical wall construction 12 incorporates, integrally formed therewith, external fins 14 and internal fins 16.

As illustrated, the external fins 14, which are integrally formed with the cylindrical tube wall 12, may be of a generally helical configuration. Similarly, the internal fins which protrude into the flow passageway 18 of the heat exchanger tube 10 are also of a helical configuration.

In order to optimize the heat transfer capacity of the heat exchanger tube, particularly when the tube is to be employed in a direct expansion evaporator of a mechanical refrigeration system, extensive experimentation and actual testing pursuant to the invention has been undertaken in order to derive an optimum heat exchanger tube design based on the physical and dimensional interrelationship of the external area Ao of the external fins 14 for each foot of length of heat exchanger tubing (ft^2/ft), the area of the internal fins Ai for each foot of tube length (ft^2/ft), the internal cross-sectional flow area Aix of the heat exchanger tube 10 (ft^2), and the lead angle θ of the internal helical fins measured relative to the longitudinal axis of the heat exchanger tube (degrees). Through suitable correlation of the dimensional interrelationships of these heat exchanger tube design parameters, extensive experimental test data has indicated that the thermal performance of shell-and-tube type direct expansion evaporators for mechanical refrigerator systems can be predicted within predetermined bounds so as to

allow for a heat exchanger tube design which considers the operating conditions of the cooler and provides an optimized heat transfer performance over the most likely employed range of operating conditions for such evaporators.

Basically, the physical design criteria for the heat exchanger tube 10 takes into consideration the operating conditions of the cooler; in effect, wherein

- $\dot{m}$ = refrigerant mass flowrate per tube lbm/hr
- ΔX = refrigerant quality change
- Refrigerant
- SST = refrigerant saturated exit temperature from the tube.

The design for the heat exchanger tube is adapted for use when the heat exchanger tubes are utilized to boil and superheat the refrigerant flowing within the tubes (approximately 8 to 10°F superheat).

In essence, the heat exchanger tube 10, based on the foregoing operating conditions of a cooler which is employed in the direct expansion evaporators of mechanical refrigeration systems, employs dimensional parameters in the design of the heat exchanger tubes, based on each unit of tube length (L) as measured in feet. These dimensional parameters are as follows:

The outside heat transfer area Ao(ft^2/ft) for the heat exchanger tube 10, which is measured as the total heat transfer surface Ao of the external fins 14 for each foot of tube length L.

The internal heat transfer area of the tube 10 which, in effect, is the total surface area Ai (ft^2/ft) of the internal fins 16 for each foot of tube length L, the lead angle θ of the internal fins, in degrees, measured relative to the longitudinal axis of the heat exchanger tube 10;

and the cross-sectional flow area Aix (ft^2) of the heat exchanger tube 10.

Thus, inventively, the following geometrical relationships have imparted optimized heat transfer characteristics to the heat exchanger tube 10, when maintained within the following parameters:

$$4.60 \leq \frac{Ai}{\sqrt{Aix}} \leq 6.20$$

$$30^\circ \leq \theta \leq 60^\circ$$

$$1.5 \leq \frac{Ao}{Ai} \leq 5$$

Moreover, the following tube geometries, utilizing the above dimensional parameters, have been found to be an optimization over prior art heat exchanger tube designs:

$$4.25 \leq \frac{Ai}{\sqrt{Aix}} \leq 6.20$$

$$40^\circ \leq \theta \leq 50^\circ$$

$$1.5 \leq \frac{Ao}{Ai} \leq 5$$

The present invention distinguishes with respect to prior art heat exchanger tube designs in that the dimensional proportions of Ao, Ai, Aix, and θ are uniquely employed in a manner which will optimize the heat transfer capacity of the heat exchanger tube 10, which is of particular significance when employed in the direct expansion shell and tube evaporator of a mechanical refrigeration system.

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In effect, an optimal interrelationship has been found between Ao, Ai, and Aix which will vary with θ. Moreover, the optimal operating range for each heat exchanger tube has also been shown to vary with θ. Consequently, set forth herein is the physical and dimensional correlation between Ao, Ai, Aix and θ which is applicable over the optimum operating range for each heat exchanger tube; for example, the optimum operating range for a heat exchanger tube having $\theta = 45°$ is somewhat different from the optimum operating range for a heat exchanger tube having $\theta = 60°$. The same relationship between Ao, Ai and Aix which is applicable for the heat exchanger tube having $\theta = 45°$ has been found to be applicable for a tube having $\theta = 60°$.

In summation, the invention sets forth a novel geometrical interrelationship for the various dimensional parameters of a heat exchanger tube which differs from those commercially available, inventively utilizing a simplified mathematical computation and design method which is not contemplated in the prior art.

While there has been shown and described what is considered to be a preferred embodiment of the invention, it will of course be understood that various modifications and changes in form or detail could readily be made without departing from the spirit of the invention. It is therefore intended that the invention be not limited to the exact form and detail herein shown and described, nor to anything less than the whole of the invention herein disclosed as hereinafter claimed.

WHAT IS CLAIMED IS:

1. A metal heat exchanger tube providing for optimized heat transfer characteristics, said metal tube comprising an integral external fin structure; and an integral internal helical fin structure defining a predetermined helix lead angle measured relative to the longitudinal central axis of the tube, the dimensions of the external and internal fin surface areas for each unit of tube length, the internal cross-sectional flow area of said tube, and said internal fin lead angle being geometrically correlated within predetermined parameters to optimize the heat transfer characteristics of said tube.

2. A heat exchanger tube as claimed in claim 1, wherein said external and internal fin area dimensions define, respectively, the external and internal heat transfer area for each unit of tube length.

3. A heat exchanger tube as claimed in claim 2, wherein said tube is geometrically correlated in that the ratio of the heat transfer area of said internal fins relative to the square-root of the internal cross-sectional flow area of said tube is within the range of about 4.60 to 6.20; the ratio of heat transfer area of said external fins relative to the heat transfer area of said internal fins is within the range of about 1.5 to 5.0; and said helix lead angle of the internal fins is within the range of about 30° to 60°.

4. A heat exchanger tube as claimed in claim 3, wherein the ratio of the heat transfer area of said internal fin relative to the square-root of the internal cross-sectional flow area of said tube is within the range of about 4.25 to 6.20; and wherein the helix lead angle of the internal fins of said tube is within the range of about 40° to 50°.

5. A heat exchanger tube as claimed in claim 1, wherein said tube is utilized for boiling and superheating a refrigerant conducted through said tube.

6. A heat exchanger tube as claimed in claim 5, wherein said refrigerant is superheated to a temperature of about 8 to 10°F.

7. A heat exchanger tube as claimed in claim 1, wherein said tube comprises a component of a direct expansion evaporator.

8. A heat exchanger tube as claimed in claim 1, wherein said external fin comprises a continuous helical fin.

9. A method of forming a metal heat exchanger tube providing for optimized heat transfer characteristics, comprising forming an integral external fin on said tube; and forming an integral internal helical fin within said tube defining a predetermined helix lead angle measured relative to the longitudinal central axis of said tube, wherein the dimensions of said external and internal fin surface area for each unit of tube length, the internal cross-sectional flow area of said tube and of said helix lead angle are geometrically correlated within predetermined parameters to thereby optimize the heat transfer capability of said tube.

10. A method as claimed in claim 9, wherein said external and internal fin dimensions define, respectively, the external and internal heat transfer areas for each unit of tube length.

11. A method as claimed in claim 10, wherein said tube is geometrically correlated so that the ratio of the heat transfer area of said internal fins relative to the square-root of the internal cross-sectional flow area of said tube is within the range of about 4.60 to 6.20; the ratio of the heat transfer area of said external fin relative to the

heat transfer area of said internal fin is within the range of about 1.5 to 5.0; and said helix lead angle of the internal fin is within the range of about 30° to 60°.

12. A method as claimed in claim 11, wherein the ratio of the heat transfer area of said internal fin relative to the square-root of the internal cross-sectional flow area of said tube is within the range of about 4.25 to 6.20; and wherein the helix lead angle of the internal fin of said tube is within the range of about 40° to 50°.

13. A method as claimed in claim 9, wherein said tube is utilized for boiling and superheating a refrigerant conducted through said tube.

14. A method as claimed in claim 13, wherein said refrigerant is superheated to a temperature of about 8 to 10°F.

15. A method as claimed in claim 9, wherein said tube comprises a component of a direct expansion evaporator.

16. A method as claimed in claim 9, wherein said external fin is formed as a continuous helical fin.

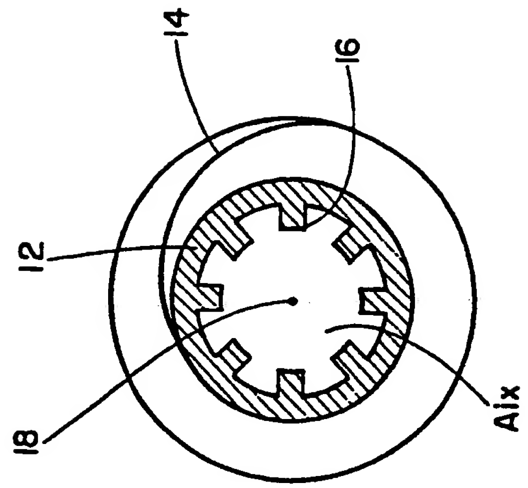

FIG.2

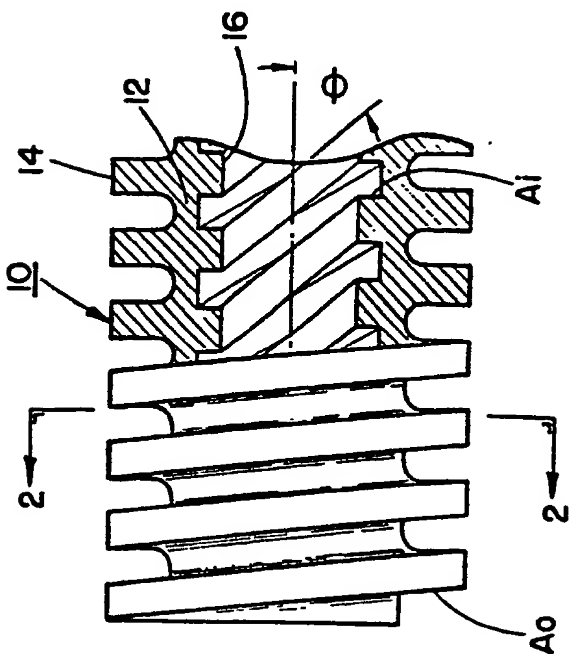

FIG.1